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# Constraining the Heliosphere: The Need for High-Resolution Observations of Nearby Interstellar Matter

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**Abstract.** High-resolution ultraviolet observations of nearby bright and faint stars are required to evaluate changes in the past and future galactic environments of the Sun, and the possibly impact of these changes on the interplanetary environment at 1 AU (around the Earth). The boundary conditions of the heliosphere and interplanetary environments are constrained by the characteristics of the surrounding interstellar material (ISM), which changes on timescales of  $10^3$ – $10^5$  years. An increase in the density of the interstellar cloud surrounding the solar system to  $10 \text{ cm}^{-3}$  decreases the heliosphere radius by about an order of magnitude. UV observations of nearby stars at high spectral resolution ( $>300,000$ ) and high signal-to-noise are required to evaluate future modifications to heliosphere properties by the ISM.

## 1. Introduction

High-resolution ultraviolet observations of nearby bright and faint stars are required to evaluate changes in the past and future galactic environments of the Sun, and the possibly impact of these changes on the interplanetary environment at 1 AU (around the Earth) and in the outer solar system.

## 2. The Heliosphere, Interstellar, and Interplanetary Matter

The interplanetary environment around the Earth and the boundary conditions of the heliosphere depend on the physical properties of the interstellar cloud surrounding the solar system (known as the “Local Interstellar Cloud”, or LIC). These boundary conditions vary with the space motions of the Sun<sup>1</sup> ( $\sim 13.5 \text{ km s}^{-1}$ ) and interstellar clouds ( $0$ – $30 \text{ km s}^{-1}$ ) through the Local Standard of Rest (LSR). The primary visitors from beyond the heliopause are neutral atoms, large dust grains (radii  $>0.20 \mu\text{m}$ , Frisch et al. 1999), and cosmic rays with energies  $>1 \text{ GeV}$ . Presently  $\sim 98\%$  of the diffuse material in the solar system is the neutral component of interstellar gas which flows relatively freely through the heliopause region. The solar wind plasma and interstellar neutral densities are equal at  $\sim 6 \text{ AU}$  because of the  $1/R^2$  falloff in solar wind density. The solar wind shields Earth

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<sup>1</sup>The LSR velocity used here is the Hipparcos value, corresponding to a solar motion towards the galactic coordinates  $l=27.7^\circ$ ,  $b=32.4^\circ$  at the velocity  $V=13.4 \text{ km s}^{-1}$  (Dehnen & Binney 1998).

from the low pressure and low density interstellar cloud around and within the solar system ( $P_{\text{thermal}} \sim 2500 \text{ cm}^{-3} \text{ K}$ ). Variations in the properties of the cloud surrounding the solar system yield variations in the heliosphere configuration and the amount of ISM in the inner solar system.

The heliopause location and heliosphere configuration depend on the relative ram pressures of the solar wind and ISM (Holzer 1989). The current boundary conditions of the heliosphere are a relative Sun-cloud velocity of  $\sim 26 \text{ km s}^{-1}$ ,  $n(\text{HI}) \sim 0.24 \text{ cm}^{-3}$ ,  $n(\text{e}) \sim 0.13 \text{ cm}^{-3}$ ,  $T \sim 7,000 \text{ K}$ ,  $X(\text{H}) = 0.31$  and  $X(\text{He}) = 0.48$ , based on radiative transfer models of ISM within 3 pc, and pickup ion and ISM absorption data (Slavin & Frisch 2002). Today the heliosphere radius is large ( $\sim 150 \text{ AU}$ ) and varies with the solar cycle.

Increasing the ISM neutral density to  $10 \text{ atoms cm}^{-3}$  has been shown to contract the heliopause radius by an order of magnitude and the heliopause becomes Rayleigh-Taylor unstable from solar wind mass-loading (Zank & Frisch 1999). This change in the heliosphere size would modify the 1 AU interplanetary environment of the Earth. The flux of interstellar neutrals at the Earth's orbit increases to  $\sim 2 \text{ cm}^{-3}$ , and the heliopause radius contracts to  $R \sim 10\text{--}14 \text{ AU}$ , and outer planets are exposed to the raw ISM, dramatically altering the interplanetary environment of the outer solar system.

### 3. Variations in Properties of ISM Surrounding the Solar System

The Sun is embedded in a cluster of interstellar cloudlets flowing outwards from the region of the Loop I superbubble. High resolution ground observations of CaII (resolution  $0.3\text{--}1.0 \text{ km s}^{-1}$ ) show that the ISM flow past the solar system contains at least six distinct velocity component groups suggestive of separate clouds. About 96 components are observed towards 60 nearby stars. Several of the nearest stars show  $\sim 1$  component per  $1.4\text{--}1.6 \text{ pc}$ . CaII component velocities towards nearby stars exhibit random velocities (rms dispersion  $\sigma \sim 5 \text{ km s}^{-1}$ ) distributed about a bulk flow velocity with upstream direction towards Loop I. In the LSR, the bulk flow velocity corresponds to a motion of  $-17.0 \text{ km s}^{-1}$  with an upstream direction of  $l = 2.3^\circ$ ,  $b = -5.2^\circ$  (Frisch et al. 2002, F02).

Cloud velocity is a proxy for cloud structure. Typical relative Sun-ISM velocities of  $0\text{--}40 \text{ km s}^{-1}$  (or more) are to be expected. An encounter with a 'new' cloud is thus possible every  $\sim 25,000$  years, and the potential for variations in the Galactic environment of the Sun exists for even shorter timescales.

Variable boundary conditions yield variable heliosphere properties. One hundred thousand years ago the Sun was immersed in the interior of the Local Bubble ( $T \sim 10^6 \text{ K}$ ,  $n_p \sim 0.005 \text{ cm}^{-3}$ ), and the heliosphere radius was similar to today but with no interstellar neutrals inside of the solar system (e.g. Mueller et al. 2002). The Sun must have emerged from the Local Bubble interior and entered the cloud now surrounding the Sun  $2,000\text{--}10^5$  years ago (Frisch 1994). As the Sun continues to travel through the outflow of cloudlets from the Loop I region, new cloudlets will be encountered.

The nearest star  $\alpha \text{ Cen}$  ( $1.3 \text{ pc}$ ) is located near the LIC LSR upstream direction (F02), however the velocity of ISM towards  $\alpha \text{ Cen}$  differs by several  $\text{km s}^{-1}$  from the projected LIC velocity suggesting the Sun may encounter the  $\alpha \text{ Cen}$  cloudlet within  $10^4$  years. Another cloudlet with  $d < 5 \text{ pc}$  and a heliocentric

velocity of  $\sim 30 \text{ km s}^{-1}$  is located in the solar apex direction. If this cloud has  $0 \text{ km s}^{-1}$  tangential velocity, the Sun will encounter this cloud within  $\sim 1\text{--}2 \times 10^5$  years (F02).

#### 4. Advantage of High-Resolution UV data

Evaluating possible changes in the boundary conditions of the heliosphere requires UV observations of the individual cloudlets near the Sun, since the required resonance transitions of dominate ions are not accessible from the ground. The tag which identifies individual cloudlets is component velocity, and high resolution optical CaII data show the component structure of interstellar clouds is undersampled in the UV at resolutions of  $3 \text{ km s}^{-1}$ . Welty et al. (1996) have shown a crowding of optical components in velocity space, such that the number of detected components increases exponentially with improved instrumental resolution. As a result, observations at the resolution of HST GHRS and STIS appear to miss over 60% of the absorption components. High resolution and high signal-to-noise observations in low column density sightlines ( $< 10^{18} \text{ cm}^{-2}$ ) towards nearby stars provide the best opportunity to resolve individual cloudlets free from the well-known but difficult-to-specify uncertainties resulting from blended components.

Optical observations of CaII towards the star  $\alpha$  Oph (14 pc) provide an example of the gains expected from improved UV resolution. For resolution  $\sim 10^6$ , UHRS data show four absorption components, compared to three components found at the lower resolution of 250,000 (e.g. Crawford & Dunkin 1995, Welty et al. 1996, Crawford 2001). Doppler b-value varies from 1.06 to 4.04 for the four components (or  $T=2700 \text{ K}$  to  $39000 \text{ K}$ , if no turbulence, Crawford 2001). The weak CaII feature towards  $\alpha$  Oph at  $-31.8 \text{ km s}^{-1}$  is formed in a cloud within 5 pc of the Sun (F02), and the b-value is alternately reported as  $1.5 \text{ km s}^{-1}$  and  $4.0 \text{ km s}^{-1}$  in the analysis of UHRS data. This difference emphasizes that high resolution data must also be high signal-to-noise data to remove uncertainties in interpreting observations of very low column density cloudlets.

Separating turbulence from thermal broadening requires UV observations with resolutions  $\sim 1 \text{ km s}^{-1}$ , and understanding the ionization and densities of the individual components requires resolving the component structure for a range of ions (e.g. FeII, MgII, MgI). Resolving out possible cold ( $100 \text{ K}$ ) cloudlets embedded in the flow of ISM past the Sun requires resolutions on the order of  $10^6$ . Such high resolution will permit determining the thermal width of MgI lines in cool neutral ( $100 \text{ K}$ ,  $b=0.26 \text{ km s}^{-1}$ ) versus warm partially ionized ( $T=7000 \text{ K}$ ,  $b=2.2 \text{ km s}^{-1}$ ) cloudlets, so that the physics of MgI in the local ISM (i.e. radiative versus dielectronic recombination) can be resolved.

Factor of two or greater variations in FeII abundances are seen in cloudlets observed towards nearby stars, showing that small-scale structure and pressure variations remain to be discovered in the immediate galactic environment of the Sun with high-resolution UV data.

## 5. Conclusions

The morphology of nearby ISM ( $< 30$  pc), and interstellar pressure variations affecting the heliosphere and interplanetary medium surrounding the Earth, *can only be found* from high-resolution ( $\lambda/\delta\lambda > 300,000$ ) observations of interstellar absorption lines in the ultraviolet wavelength band (912 — 3000 Å). The relative simplicity of sightlines to nearby stars, combined with high-resolution high signal-to-noise UV data, provides the best opportunity for obtaining accurate abundances and cloud properties for interstellar clouds.

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